Suppression of parasitic lasing in large-aperture Ti:sapphire laser amplifiers

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Transverse, parasitic lasing has been observed in several large Ti:sapphire disk amplifiers. It severely limits the signal gain and the pulse energy that can be extracted from the amplifier. We have developed a technique for suppressing these parasitic lasing modes based on index matching the crystal edges with an absorbing doped polymer thermoplastic. The parasitics are completely suppressed for the range of aperture sizes and pump fluences studied here. A comparison of the amplifier performance before and after edge cladding is presented for several Ti:sapphire crystals.

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Chirped-pulse amplified laser systems have evolved and matured extensively over the past 13 years. The two gain media that are most commonly employed for chirped-pulse amplification are Nd:glass and Ti:sapphire. Extremely high peak intensities have been achieved in both of these systems. Nd:glass produces longer, more energetic pulses than Ti:sapphire because its saturation fluence is approximately five times larger[1] ($\approx$5 compared with $\approx$1 J/cm^2), but its gain bandwidth will support only pulses that are more than an order of magnitude longer in duration (several hundred femtoseconds, compared with $\approx$20 fs for Ti:sapphire). The scaling of a chirped-pulse amplified Nd:glass system to very high intensity ($\approx 10^{21}$ W/cm^2) was achieved with large-aperture disk amplifiers (46-cm diameter) at the Petawatt Laser Project, Lawrence Livermore National Laboratory.[2] In Ti:sapphire, a focused intensity of 5×10^{19} W/cm^2 was achieved with energetic 120-fs pulses.[3] More recently, scaling of Ti:sapphire chirped-pulse amplifier systems to intensities higher than 10^{19} W/cm^2 was accomplished, primarily by reduction of the amplified pulse width,[4,5] because attainment of significantly higher pulse energies has been limited by the availability of large-aperture crystals with good optical quality. Here we report preliminary results for what is to our knowledge the largest Ti:sapphire laser disk amplifier ever produced.

Parasitic lasing is the most important laser physics issue that must be addressed in the design of large-aperture high-gain amplifiers. This problem was originally identified and studied in the mid-1960's for ruby lasers[6] and later in the 1970's for large-aperture Nd:glass disk amplifiers.[7–10] Parasitic lasing is due to the formation of a laser cavity by Fresnel reflections at the material interfaces of the gain medium. In general, many complex cavity configurations with multiply reflected ray pathways can lase simultaneously. In Nd:glass disks without special edge claddings the magnitude of the Fresnel reflections is of the order of $\approx$5%, so the onset of parasitic lasing typically becomes a problem when the transverse gain approaches e^3 ($\approx$20).[7] Above the parasitic lasing threshold the gain is clamped, and no additional energy can be stored in the amplifier. Fortunately, for Nd:glass many suitable materials are available for index matching near $n = 1.5$, and parasitics have successfully been suppressed in disks that are >30 cm in diameter.[9,10] The significantly higher index of Ti:sapphire ($n = 1.76$) and its large transverse gain (in part due to the longitudinal pumping geometry) present special problems for parasitic suppression techniques.[11]

Measurements were performed on three different Ti:sapphire disk amplifiers. Two of the disks (designated CS1 and CS2) were grown by Crystal Systems, Inc., by the heat-exchanger method. These disks are 10 cm in diameter, with frosted, roughened edges. Disk CS1 is 1.15 cm long and has single-layer MgF_2 antireflection coatings centered at 800 nm [the residual reflectivity (R) at 800 nm is $\approx$1%, and that at 532 nm is $\approx$7%]. The 532-nm absorption coefficient (α) for CS1 is ≈ 1.87 cm^{-1}. In contrast, disk CS2 is uncoated ($R \approx 7\%$ at both 532 and 800 nm) and has a significantly lower titanium concentration ($\alpha \approx 0.85$ cm^{-1}) and a longer length ($L = 3.3$ cm). The third Ti:sapphire disk studied here, designated UC1, was grown by Union Carbide by the Czochralski method. Disk UC1 has single-layer MgF_2 coatings, a diameter of 8 cm, a length of 2.5 cm, and $\alpha \approx 1.8$ cm^{-1}.

Small-signal gain and spectral measurements were performed on the three Ti:sapphire disks described above, with a 532-nm pump laser based on a Q-switched Nd:YAG oscillator and a Nd:glass amplifier chain with a relay-imaged flat-topped beam.[3] This laser system generates as much as 15 J of energy at 532 nm with a pulse duration of $\approx$6 ns. The polarization of the 532-nm output beam is aligned along the Ti:sapphire crystal c axis, and the beam is propagated in a single pass through the center of the crystal with a diameter of $\approx$3.2 cm. The small-signal gain was monitored by two different methods. First, a stretched output pulse (800 nm, 280 ps, $\approx$40 mJ) from a Ti:sapphire regenerative amplifier was double-passed through the crystal and measured with a pyroelectric energy meter. Second, a cw laser diode (Sharp LT015MD0, 830 nm, 40 mW) was double-passed and then coupled into a multimode optical fiber (62.5-μm-diameter core) that was terminated in a fast optoelectronic converter (Tektronix Model P6701) and digital oscilloscope (Tektronix Model DSA602).

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The latter measurement allows the time dependence of the small-signal gain to be measured directly. To measure the transverse optical power spectrum of the Ti:sapphire crystal we aligned a second multimode optical fiber at the edge of the input face and oriented it to collect emission in the plane of crystal face. The output end of this fiber was coupled to a grating spectrometer with an optical multichannel analyzer and computer readout ($\approx$1-nm resolution).

Figure 1 shows the transverse optical power spectrum of crystal CS1 at high pump fluence (≈ 1.7 J/cm^2). Trace 1 in the figure indicates that the crystal is lasing in the transverse direction: The spectrum has redshifted and narrowed compared with a series of transverse spectra (not shown) recorded at lower pump fluences (as low as ≈ 0.2 J/cm^2). The onset of transverse lasing in this crystal can also be detected in the time domain. Trace 1 of Fig. 2 shows the photodiode signal recorded for the double-pass diode laser at the same fluence as for Fig. 1. The flat baseline, which is present before the green pump pulse arrives (approximately 0–10 ns), serves as an automatic calibration for the gain measurement because the propagation losses are included (i.e., by definition the net gain is equal to 1 before the arrival of the pump pulse). As the green pump pulse is absorbed by the Ti:sapphire disk, the gain rises as the integral of the pulse energy until the transverse lasing threshold is reached, whereupon the gain is rapidly depleted as the inversion is dumped by the lasing modes. The temporal dependence of the transient gain feature in Trace 1 of Fig. 2 is consistent with that which is expected for a gain-switched Ti:sapphire laser with a cavity length ($\approx$1.2 ns) and loss ($\approx$99%) predicted for the transverse lasing geometry of disk CS1. After the transverse lasing modes drop below threshold, a small residual longitudinal gain remains and persists for several microseconds (consistent with the Ti:sapphire lifetime). Close examination of a series of spectra and scope traces indicates that the threshold for transverse lasing occurs at ≈ 0.7 J/cm^2. The asterisks shown in Fig. 3 plot the exponential gain (g_0L, where g_0 is the small-signal power gain coefficient averaged over length L of the amplifier) versus the 532-nm pump fluence incident upon crystal CS1. Above ≈ 1 J/cm^2 the measured g_0L product exhibits a large deviation from the linear dependence predicted by simple theory[12]:

$$g_0L = \frac{\sigma_e F_p}{h\nu_p}[1 - \exp(-\alpha_p L)], \tag{1}$$

where σ_e is the emission cross section, α_p is the pump absorption coefficient, F_p is the pump energy density, and $h\nu_p$ is the pump photon energy. [For crystal CS1 a line with a slope of 0.67 is predicted by Eq. (1).] The deviation from the linear theory observed in Fig. 3 is due to a time shifting of the transient gain peak as the transverse lasing occurs increasingly earlier with increased green pump energy. In other words, when the regenerative amplifier pulses that we use to measure g_0L (asterisks in Fig. 3) arrive at a fixed time, the magnitude of the gain that they sample varies with green pump pulse energy because the gain peak shifts forward in time as the lasing threshold is reached sooner. The crosses in Fig. 3 show that this effect can be partially compensated for by careful retiming of the arrival of the regenerative amplifier pulses with respect to the green pump pulses to subnanosecond accuracy for each pump fluence. With retiming, significant deviations from linearity are not observed until the pump fluence exceeds ≈ 1.5 J/cm^2. However, the use of timing to control gain competition between the transverse lasing mode and the amplified signal pulse is not practical for implementation in an actual, reliable laser system because the requirement for reducing timing jitter on such a multistage amplifier system would be nearly impossible to achieve. For higher pump fluences (above 2 J/cm^2) the deviation from linearity and

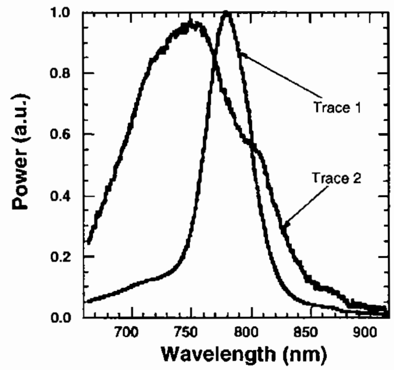

Fig. 1. Transverse optical power spectra of crystal CS1 at high pump power. Trace 1, without cladding; trace 2, with cladding.

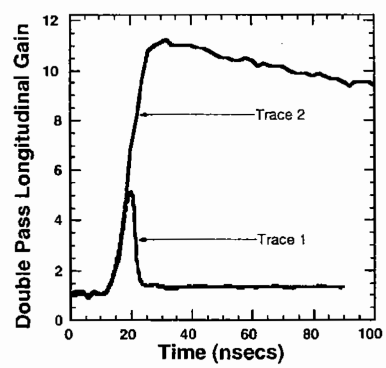

Fig. 2. Oscilloscope record of the double-passed diode laser at the same fluence as in Fig. 1.

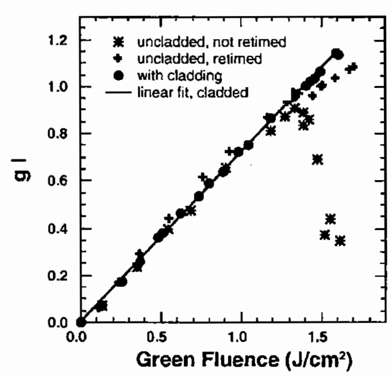

Fig. 3. Exponential gain (g_0L) versus 532-nm pump fluence incident upon crystal CS1.

Table 1. Summary of Gain Parameters for Several Disk Amplifiers

Disk	α (cm^{-1})	L (cm)	Transverse Lasing Threshold (J/cm^2)	Gain at Threshold, g (cm^{-1})	Slope of gl versus Pump Fluence (cm^2/J)
CS1	1.87	1.15	0.74	0.54	0.70 ± 0.02
CS1[a]	1.87	1.15	>1.8	–	0.72 ± 0.0006
CS2	0.85	3.30	>1.8	–	0.73 ± 0.01
UC1	1.80	2.50	1.14	0.68	0.65 ± 0.02
UC1[a]	1.80	2.50	>1.8	–	0.62 ± 0.02

[a]Cladding has been applied for this set of measurements.

the timing sensitivity are expected to become even more severe.

Next, we explored techniques for suppression of the transverse lasing. Simple application of black ink to the frosted edges of the crystal yielded only a minor increase in the lasing threshold. Cladding crystal CS1 with an index-matched thermoplastic polymer (Cargille Laboratories catalog number 24170) doped with an absorber (powdered ink from a Canon toner cartridge, catalog number F41-9502-740) produced much more significant results. For 800-nm light, the thermoplastic is highly transmissive and has an index of refraction (n) of 1.6849. The Fresnel reflection at the Ti:sapphire interface is thus estimated to be $\approx 0.048\%$, which implies that transverse, parasitic lasing should not occur across the input face until the transverse gain is ≈ 2100. In actuality, cladded crystal CS1 did not lase, even at the maximum pump fluence used here (≈ 1.61 J/cm^2), for which the transverse gain is estimated to be 6500. This result can be explained as follows: Without cladding, the lasing threshold for crystal CS1 is ≈ 0.7 J/cm^2, which corresponds to a transverse gain of ≈ 64 and an effective cavity reflectivity of $\approx 1.5\%$ ($1/64 \times 100$). Inasmuch as the Fresnel reflection at the Ti:sapphire–air interface is $\approx 7\%$, we infer that scattering at the frosted disk edge contributes additional transmission loss to the transverse cavity of the order of $1.5/7 = 0.214$. Using the latter factor in conjunction with the estimated cladded reflectivity (0.048%) yields an estimate that the transverse lasing threshold for cladded crystal CS1 should occur at a gain of ≈ 9700, corresponding to a pump fluence greater than the maximum used here.

Figures 1–3 also show the spectral, temporal, and small-signal gain characteristics for cladded crystal CS1. Trace 2 of Fig. 1 shows a transverse fluorescence spectrum with a center wavelength and bandwidth that are typical for below-threshold optically pumped Ti:sapphire crystals.[13] Trace 2 of Fig. 2 shows the temporal dependence of the double-passed diode laser through cladded crystal CS1. In contrast to Trace 1 in Fig. 2, which shows a short, gain-switched pulse that is indicative of parasitic, transverse lasing, Trace 2 shows a reduced fluorescence lifetime (400 ns) but no evidence of transverse lasing. The filled circles in Fig. 3 show that, when crystal CS1 is cladded and parasitic lasing is suppressed, a linear small-signal gain dependence is observed, as predicted by Eq. (1) for below-threshold Ti:sapphire amplifiers.

The set of measurements presented in Figs. 1–3 for crystal CS1 were also performed on crystals CS2 and UC1. Because of space constraints, we only briefly summarize the results here. The parasitic lasing characteristics of UC1 are similar to those of CS1 because the titanium concentrations are nearly identical. The spectra and temporal gain profiles (not shown) indicate that UC1 lases without cladding (threshold, ≈ 1.1 J/cm^2) but not after treatment with the doped thermoplastic described above. In contrast, crystal CS2 is significantly lower in concentration and does not lase under the conditions explored here. Table 1 summarizes the performance for the various crystals (cladded and uncladded) studied here.

In conclusion, we have observed that parasitic, transverse lasing in large-aperture (>3 cm) Ti:sapphire amplifiers can seriously impair the performance of the amplifiers. Among the problems are limited extraction efficiency and restrictive timing requirements. In general, lower titanium concentrations and longer crystal lengths are preferred because they help to avoid parasitic lasing to a certain extent. In addition, we have shown that suppression of the parasitics can be accomplished by careful index matching at the disk edges. Recently we pumped the CS2 amplifier disk with as much as 100 J of green in a 6-cm aperture. Parasitic lasing was observed under these conditions, but several techniques used in combination were successfully employed to suppress it.

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